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PRELIMINARY FLIGHT RESULTS OF A FLY-BY-THROTTLE EMERGENCY FLIGHT CONTROL SYSTEM ON AN F-15 AIRPLANE

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Abstract

A multi-engine aircraft, with some or all of the flight control system inoperative, may use engine thrust for control. NASA Dryden has conducted a study of the capability and techniques for this emergency flight control method for the F-15 airplane. With an augmented control system, engine thrust, along with appropriate feedback parameters, is used to control flightpath and bank angle. Extensive simulation studies have been followed by flight tests. This paper discusses the principles of throttles-only control, the F-15 airplane, the augmented system, and the flight results including actual landings with throttles-only control.

Nomenclature

CAS	control augmentation system
CG	center of gravity
DEEC	digital electronic engine control
EMD	engine model derivative
HIDEC	Highly Integrated Digital Electronic Control

HUD	heads up display
PCA	propulsion controlled aircraft
V	airspeed, kts
α	angle of attack, deg
γ	flightpath angle, deg
ϕ	bank angle, deg

Introduction

In an emergency situation, throttles can be used to augment or replace aircraft flight control systems. Aircraft flight control systems are extremely reliable because of the multiple control surfaces, hydraulic systems, sensors, control computers, and control cables used to achieve high levels of control system redundancy and reliability. However, there are rare occasions when potentially disastrous flight control system failures do occur. This is particularly true for military airplanes operating in a hostile environment. At such times, any other form of flight control, including propulsion, would be welcome.

Some aircraft with multiple engines may be controlled to a rudimentary degree with the throttles. The use of differential thrust induces yaw and the normal dihedral effect results in roll. Many transport airplanes exhibit nose-up pitching moments from thrust that may be useful for pitch control. In addition, most airplanes have positive speed stability (if speed is increased, the airplane will climb, and vice versa). Airplanes with total hydraulic system failures have been flown for substantial periods with only engines for control.¹ The following are examples of loss of hydraulic power:

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- A B-747 aircraft lost its entire hydraulic system because of a pressure bulkhead failure. It was flown for almost an hour using throttle control, but the crew were forced to learn by trial and error, and the plane eventually hit a mountain.
- An uncontained engine failure on a DC-10 caused the loss of all hydraulics. The crew used throttles for control under extremely difficult circumstances and were able to execute an emergency crash landing at an airport, and many lives were saved.

In other cases hydraulic loss caused partial loss of flight controls:

- A C-5A cargo airplane had a major structural failure that caused loss of all hydraulics to the tail. This airplane was flown for 1/2 hr with the throttles, but on a landing attempt, the airplane hit the ground short of the runway, broke up, and all aboard were killed in the resulting fire.
- B-52 airplanes have experienced two cases of total loss of hydraulic power to the rudder and elevator. Thrust and wing spoilers were used for pitch control. In one case, the crew tried to land the airplane, and hit very hard, breaking off the nose section on impact. The rest of the airplane was destroyed by fire, but the entire crew survived. In the second instance, procedures developed as a result of the first accident were used. The B-52 had a hard landing, but was repairable.

The NASA Dryden Flight Research Facility has been conducting flight, ground simulator, and analytical studies to investigate the use of the propulsion system for emergency flight control. One objective, determining the degree of control power available for various classes of airplanes, has shown a surprising amount of control capability for many airplanes. The second objective was to provide awareness of and techniques for manual throttles-only control.¹ Airplanes studied to date include the B-720, MD-11, F-15, B-727, T-38, Learjet, and B-747. The third objective is to investigate possible control modes that could be developed for future airplanes.²

NASA Dryden and McDonnell Douglas Aerospace Company (MDA, St. Louis, MO) developed an augmented control system for the F-15 which uses feedback to provide throttle commands for emergency flight control. An initial flight evaluation of this propulsion controlled aircraft (PCA) system has recently been flown. Comparisons of flight and simulation results of the F-15 airplane flown with manual throttles-only control are given in ref. 3.

This paper reviews the principles of throttles-only control, the design of the PCA system, and preliminary

results of the first flight evaluation of a PCA system, including landings without the use of flight controls. Also presented is how the PCA system performs at conditions beyond the design envelope.

Principles of Throttles-Only Control

The principles of throttles-only flight control, presented in refs. 1 and 3, will be reviewed here, using examples for the F-15 airplane.

Roll: Differential thrust generates sideslip, which, through dihedral effect, results in roll rate. Roll rate is controlled to establish a bank angle which results in a turn and change in aircraft heading. Full differential thrust for the F-15 yields a roll rate of about 12 to 15 deg/sec.

Pitch: Pitch control due to throttle changes is more complex. There are several effects that occur on the F-15.

1. Flightpath angle change due to speed stability. All stable airplanes, including the F-15, exhibit positive speed stability. For a short time (approximately 15 sec), a thrust increase will cause a speed increase, which will cause a lift increase which causes a pitch rate increase, and a climb (if allowed to continue, this effect will be oscillatory, see phugoid, no. 4). The degree of change to the flightpath angle is proportional to the difference between the initial trim airspeed and the current airspeed, hence, the flightpath angle tends to increase as speed increases.
2. Pitching moment due to thrust line offset. If the engine thrust line does not pass through the center of gravity (CG), there will be a pitching moment introduced by thrust change. For many transport aircraft, the thrust line is below the CG, and increasing thrust results in a desirable nose-up pitching moment, the magnitude being a linear function of the thrust change. This is the desirable geometry for throttles-only control, because a thrust change immediately starts the nose in the same direction as that needed for the long-term flightpath angle change. The effect is more a function of change in thrust than of change in speed, and occurs near the time of the thrust increase. For the F-15, the thrust line passes within ± 1 in. of the vertical CG, depending on fuel quantity, and this effect is small.
3. Flightpath angle change due to the vertical component of thrust. If the thrust line is inclined to the flightpath, as is commonly the case, an increase in thrust will cause a direct increase in vertical velocity, i.e., rate of climb, and a resulting increase

in flightpath angle. For a given aircraft configuration, this effect will increase as angle of attack increases (i.e., as speed decreases).

For the F-15, the combined effects of the engine thrust produce a nose-up pitching response of about 2.5 deg/sec for a throttle step from trim to intermediate power on both engines.

4. **Phugoid.** The phugoid is the longitudinal long-period oscillation of an airplane. It is a motion in which kinetic and potential energy (speed and altitude) are traded. The phugoid oscillation is excited by a pitch, or velocity change, and will have a period of approximately one minute, and may or may not damp naturally. Properly sized and timed throttle inputs can be used to damp unwanted phugoid oscillations.¹

Speed Control: Once the flight control surfaces of an airplane are locked at a given position, the trim airspeed of most airplanes is only slightly affected by engine thrust. Retrimming to a different speed may be achieved by other techniques, such as variable stabilizer control, CG control, lowering of landing gear, and flaps, etc. In general, the speed must be reduced to an acceptable landing speed; this implies developing nose-up pitching moments. Methods for doing this include moving the CG aft, lowering the flaps, and extending the landing gear. For the F-15, moving the air inlets to the full-up emergency position reduces the trim speed by at least 20 kts, and lowering the flaps lowers the trim speed by at least 30 kts.

Trim speed is also affected by changes in weight. As weight is reduced (such as by burning fuel), the lift remains constant, so the airplane tends to climb. To maintain level flight, the throttle setting must be reduced, which reduces speed. On the F-15, this effect reduces trim speed by approximately 1 kt every 2 min.

Stability: The flight controls-failed stability of an airplane is also an important consideration for throttles-only control. Large transport airplanes typically have good basic static stability. Yaw dampers may be used for increasing the dutch roll mode stability, but good pitch, roll, and yaw static stability is usually built in. This stability remains if the flight control system should be lost. For fighter airplanes, the airframe may have lower levels of static stability, with adequate stability being achieved with mechanical and/or electronic stability augmentation. Thus in the case of flight control system failure in a fighter, the basic stability may be considerably reduced, and the control requirements for a PCA system will be more difficult. (The previous comments do not apply to the long-term phugoid stability which will likely be a problem for both fighter and transport aircraft).

Airplane Description

The F-15 airplane (Fig. 1) is a high-performance air superiority fighter airplane with a maximum Mach capability of 2.5. It has a high wing with 45° of sweep and twin vertical tails. The two afterburning turbofan engines are mounted close together (4.25 ft apart at the nozzles) in the aft fuselage. Air inlets for the engines are located on the fuselage sides, ahead of the wings.

Engines

The NASA F-15 is powered by F100 engine model derivative (EMD) engines, designated PW1128 by the engine manufacturer. These engines feature a 3-stage fan and a 9-stage compressor, each driven by a 2-stage turbine. A mixed flow augmentor exhausts through a variable-area convergent-divergent nozzle. The PW1128 is a derivative of the F100-PW-220 engine, and features an improved fan, higher turbine temperature capability, and a 15-segment augmentor.

The digital electronic engine control (DEEC) system controls the F100 engine. Closed-loop control of engine pressure ratio and airflow is provided at intermediate power and above. At lower power, fan rpm is controlled as a function of throttle angle. At low power settings with the landing gear extended, the nozzle opens to reduce thrust. The DEEC transmits engine parameters in digital format to the data bus, and also receives inputs for throttle commands on the data bus.

Because of the development nature of the PW1128 engines used in the NASA F-15, the DEEC software has some nonproduction effects, one of which is a slow decay of thrust at low power settings. An engine model developed by MDA accurately represents the dynamic response of the PW1128 engines at the low-speed-low-altitude condition.

Inlets

The F-15 is equipped with variable-geometry 2-dimensional external compression horizontal ramp inlets. Since these inlets are well forward and outboard of the aircraft CG, pitching, rolling, and yawing moments are developed by the inlet aerodynamics as engine airflow changes. Although these forces and moments are small in conventional flight, they become significant when the flight controls are locked. If hydraulic pressure to the actuators is lost, the inlet ramps both drift to a full-up position. This was the condition used for all F-15 PCA tests.

Flight Control System

The F-15 has a mechanical flight control system augmented by a high-authority electronic control augmentation system (CAS). Hydraulic power is required for all flight control surfaces. The NASA F-15 airplane

is equipped with a digital electronic flight control system (DEFCS) which replaced the standard F-15 analog electronic CAS. In the flight control mode (CAS off, with the mechanical system pitch and roll ratio change mechanisms set in the "emergency" fixed position) the flight control system surfaces remain stationary as long as the stick and rudder pedals are not moved.

Instrumentation

The F-15 airplane was instrumented to measure the parameters required for the throttles-only flights. All typical engine and airplane parameters were measured. Data from individual sensors and data from the digital control system data buses (each engine and the digital flight control system) were recorded on an onboard pulse code modulation system. Data were telemetered to the ground for real-time recording, analysis, and display.

The F-15 has a heads-up display (HUD) which provides flight information such as airspeed and altitude. A velocity vector symbol displays the precise flightpath relative to the ground. A HUD video camera was provided and the signal, along with the pilot's microphone (hot mike) was also telemetered to the ground.

Propulsion Controlled Aircraft System

The PCA system features on the F-15 are shown in Fig. 2. Much of the equipment used by the PCA system was previously installed on the NASA F-15 for other integrated control research as part of the Highly Integrated Digital Electronic Control (HIDEC) system,⁴ and included the digital flight control computer, the general-purpose research digital computer, the F100 EMD engines with DEECs, the cockpit HUD and control system input-output, interface equipment to allow these systems to communicate, the "emergency" flight control mode, and the data system and tape recorder. The PCA system was implemented by adding only the attitude command thumbwheel controllers in the cockpit.

Figure 3 shows the F-15 HIDEC airplane cockpit, the PCA equipment, the thumbwheel controllers, the HUD, the navigation control interface (NCI), and the switches and control panels from the PCA and HIDEC systems.

The PCA system was designed for a limited-envelope first flight evaluation of augmented throttles-only control. It was designed to function at airspeeds between 150 and 190 kts at altitudes below 10,000 ft. It was assumed that the airplane would be trimmed to the desired test conditions prior to PCA system engagement.

Figure 4 is a block diagram of the PCA system structure. All of this equipment except the thumbwheel controller panel was previously installed. The various

avionics and PCA units communicate with each other via digital data buses. The logic for the PCA control laws resides in the general-purpose research computer, in FORTRAN code. Digital inputs are received from the digital flight control system, the inertial navigation system (INS), the airdata computer, the digital engine controls, and from the pilot's pitch and roll thumbwheels. The PCA system sends throttle commands to the internal DEEC throttle command logic without driving the throttles in the cockpit. No commands are sent to the inlets during PCA operation.

Figure 5 is a block diagram of the PCA control laws. In the pitch axis, pilot thumbwheel command for flightpath angle is compared to the sensed flightpath angle, with flightpath angle rate and velocity also available as feedbacks to assist in phugoid damping. Collective (equal) thrust commands are sent to both engines to obtain the commanded flightpath. The thumbwheel flightpath command is displayed to the pilot on the HUD with the box shown in Fig. 3.

In the roll axis, the pilot bank angle command is compared with yaw rate, roll rate, and bank angle; differential thrust commands are issued to both engines to obtain the commanded bank angle.

The pitch and roll axis control laws were developed by MDA and Dryden using linear models, nonlinear simulations, and finally in full nonlinear piloted simulations.

Variable gains, filters, multipliers, and gain schedules can be selected by the pilot, and are available at most points within the PCA software. These features provide a great deal of flexibility for testing.

Numerous automatic features were installed to disengage the PCA system in case of malfunction, if the predefined limits were exceeded, or if the pilot moved the stick or throttles.

F-15 Simulations

High-fidelity simulations of the PCA system in the F-15 airplane were available at NASA Dryden and at MDA. These simulations included nonlinear aerodynamics, control systems, and nonlinear engine models as well as the PCA logic. Pilot-in-the-loop simulators were used for closed-loop pilot evaluations. Batch versions were used for open-loop system response and to develop, evaluate, and test the PCA software. The MDA simulators included a high-fidelity visual system projected onto a dome, whereas the Dryden simulation used a smaller monitor; both were adequate for the PCA evaluation. Linear models of the PCA system were also developed at MDA and at Dryden for control system development and analysis. MDA tests included a hardware-in-the-loop piloted simulation in which the

actual flight software and computers were part of the simulation.

Test Conditions and Procedures

The F-15 PCA system was tested primarily in 2 configurations; 150 kts with flaps down, and 170 kts with flaps up. Test altitudes ranged from 2300 ft (10 ft above the runway) to 15,000 ft. The pilot configured the airplane with the CAS off, and pitch and roll ratios and inlets in the "emergency" position, which is the position that would occur if hydraulic pressure were lost. The landing gear was lowered hydraulically, although it could have been lowered with the emergency pneumatic extension system. The flaps were lowered with the electric actuation system installed on the NASA F-15.

The pilot trimmed the airplane to the desired test condition with the stick, engaged the PCA system using the "couple" button on the right throttle, and operated the thumbwheels with no inputs to the stick and throttles. The flight controls remained active, but not used, as a safety feature. In some cases, the system was engaged 70 kts above its original design envelope.

Test techniques were developed to assess the throttles-only control capability of the F-15 airplane and simulation. Open-loop tests, including small controlled throttle steps were flown, and control capability was compared to the simulation.

Small step commands in pitch and roll during level flight were made when the augmented system tests were initially conducted. Once these tests were complete, combinations of pitch and roll commands were tested, and finally, simulated approaches were made. Manual control techniques were also used for comparison.

Results and Discussion

The F-15 PCA system was evaluated during a series of flights. The initial tests consisted of engaging the PCA system in level flight and observing the system operation. Later tests included response to step inputs and approaches to the runway.

Step Inputs

Numerous step thumbwheel command inputs have been made to flightpath and bank angle axes at varying weights, airspeeds, and gain combinations. These step inputs allow detailed postflight comparisons of actual flight performance with simulation predictions, and between differing flight control configurations tested. Figure 6 shows a response to a small negative flightpath angle command at 150 kts, with the flaps down. The initial throttle decrease is followed by throttle modulation to achieve the desired flightpath with minimum

overshoot. The average fan speed, a good approximation of thrust, is also shown in Fig. 6. Approximately 11 sec is required to achieve the 1.8° -decrease in flightpath angle. A comparison of the nonlinear simulation at this condition shows a slightly slower response, but reasonably good agreement with the flight data.

Roll response to a full roll step command is shown in Figs. 7(a) and 7(b). Roll control was initially poor because of low roll rate, as shown in Fig. 7(a), with 28 sec required to achieve the commanded bank angle. Only a small differential throttle command was generated by the control laws. This low roll rate was dictated by results from the hardware-in-the-loop simulation, in which higher gains caused a limit cycle oscillation. Extensive flight evaluations were then conducted to improve roll performance. After several iterations, the roll response was greatly improved by changes in gains, yaw rate filtering, and adding bank angle feedback as shown in Fig. 7(b), with the commanded bank angle being reached within 6 sec. A significant degree of differential thrust was commanded in this test. No evidence of the limit cycle oscillation was seen in the flight tests. Again, comparison to the nonlinear simulation prediction for this condition is reasonably good.

Runway Approaches

The PCA system was typically engaged on the downwind leg of approaches to the Edwards runway. Turns were made to the base leg, and onto final approach about 5 miles out. Figure 8 shows the command and actual flightpath (glide slope) and bank angle values for a low approach and PCA go-around at 150 kts. Engine throttle settings, height above the ground, and airspeed are also shown. This approach showed good control with very light turbulence. Flightpath was maintained within approximately 1° of command until the go-around was initiated. Most of the throttle motion is differential to maintain the commanded bank angle. Bank angle lags pilot inputs by approximately 3 sec. At 100 ft above the ground, as planned, the pilot initiated a go-around by moving the flightpath command up to command a climb. The system response was considered adequate by the pilot.

In a test to evaluate PCA response in ground effect, the pilot flew with PCA control to within 10 ft of the runway. The pilot decoupled the system at this point as planned, and made only a minimal stick input in the remaining 2 sec until touchdown. Figures 9(a) and 9(b) show a time history of this approach. Weather conditions included a 5-kt tailwind and very light turbulence, with occasional small upsets caused by thermals. Figure 9(a) shows 83 sec of the approach. Flightpath command varied between -1 and -2° for most of the approach, and flightpath was maintained within 0.5° of the command, except when mild

thermal activity caused a pitchup at 23 sec and again at 60 sec. Bank angle commands were generally small and bank angle was maintained, considering the 3-sec lag, within 3°. At 70 sec, the pilot increased the flightpath command to initiate a landing flare.

The last 6 sec prior to touchdown are shown in Fig. 9(b). Flightpath gradually was reduced and bank angle remained small. As the F-15 entered ground effect at about 15 ft above the ground, an increase in flightpath angle caused by increased wing lift was seen. At 10 ft, the pilot disengaged the PCA system and made a small aft stick input (seen in the stabilizer position data) to reduce the sink rate. At about 5 ft, a nose-down pitch is seen in the pitch rate and angle of attack data, because of the effect of ground effect on the fixed horizontal tail. This reduction in angle of attack, which reduces lift, causes the flightpath to remain constant for the last second. Touchdown rate of sink was about 4.5 ft/sec. The pilot made a larger aft stick input at touchdown to control de-rotation. The pilot considered the system performance to be good on this approach.

A time history of the last 56 sec of the first PCA landing is shown in Fig. 10. The conditions for this landing included an 8-kt wind down the runway, and almost no turbulence. The pilot reduced the flightpath command to 1° at an altitude of 200 ft, and to 0.4° at 80 ft, resulting in a very shallow final approach. At an altitude of 20 ft, 6 sec before touchdown the ground effect begins. With no flight control input to counter the ground effect, the nose pitched down to -1.8° at touchdown, at which point the pilot made an aft stick input to cushion the landing. The PCA system added thrust and increased airspeed by 4 kts trying to counter the pitchdown. Bank angle control and lineup was good throughout the final approach. A small correction to the right was made just before touchdown. The bank angle at touchdown was -1° and the touchdown was approximately 8 ft to the left of the runway centerline. Following this landing, another approach was made. In this case, the control tower requested a 360°-turn for spacing 6 miles from the runway. The pilot made this turn and then continued the approach and landed, all with PCA control.

Engagement at Unusual Attitudes

Another test was to engage the PCA system after the airplane was maneuvered to unusual attitudes, such as might occur with an actual loss of flight controls. Although the PCA system was not specifically designed to handle such conditions, simulation studies indicated that it could safely recover the F-15 from a range of upsets. The most severe test (Fig. 11) was initiated at 250 kts at 15,000 ft, with a 22°-nose down and 78°-bank situation. The pilot moved the inlets to the emergency

position and engaged the PCA system. The PCA system increased the right engine thrust to intermediate power; the wings were rolled level within 15 sec, the pullout reached 3 g and 320 kts, with a loss of altitude of 3000 ft. Following the pullout, the airplane entered a climb. With no pilot action and a zero bank command, the airspeed would have decayed to approximately 100 kts; in this case the pilot terminated the test at an airspeed of 150 kts.

Hydraulic System Failure Simulation

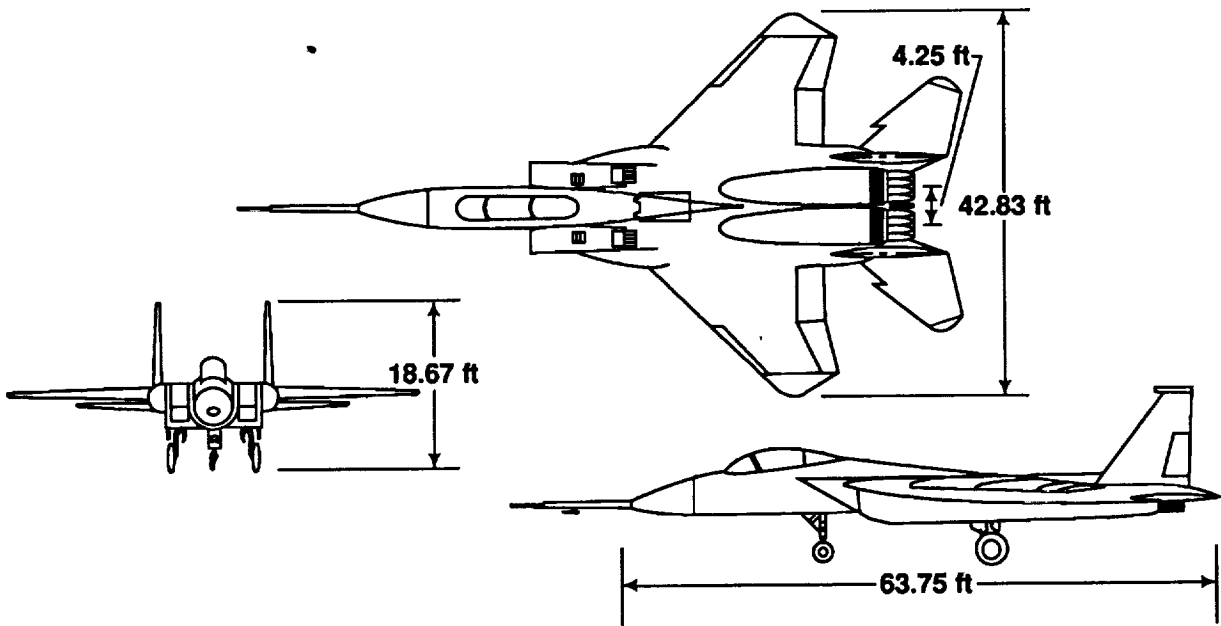
Tests were also conducted to determine the trim speed variations after a simulated hydraulic failure. Starting from 260 kts and level flight, the CAS was turned off and the inlets were switched to emergency as would occur with loss of hydraulic pressure. The PCA system was engaged, and the new trim speed was 200 kts. The flaps were then lowered electrically, and the trim speed was reduced to 160 kts. Landing gear extension caused no change in trim speed. From this condition, fuel could be burned off to achieve a 150-kt approach speed.

Concluding Remarks

The first flight evaluation of an augmented propulsion controlled aircraft system on the F-15 airplane has been conducted. An augmented throttles-only feedback control system has been shown to provide stable operation to step inputs and acceptable operation for landing approaches and actual landings. The system has also been tested at conditions beyond its design envelope, including engagement at unusual attitudes and at speeds 100 kts above approach speeds.

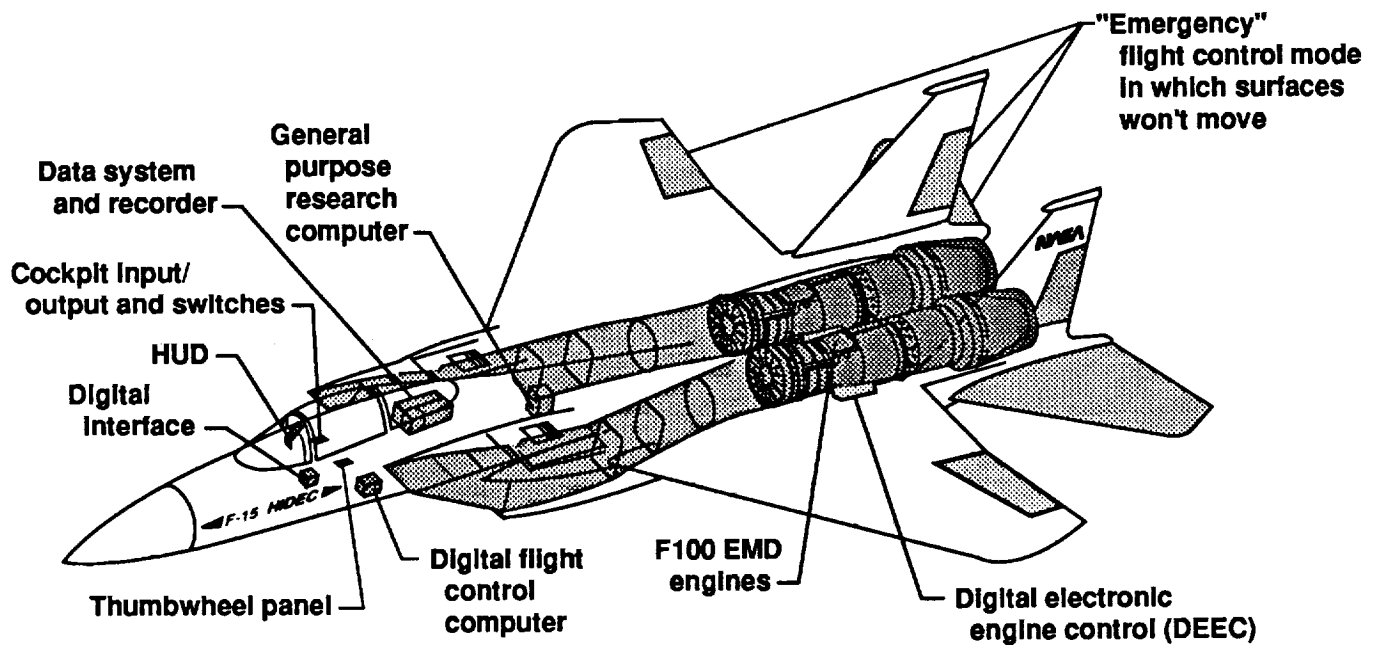
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- ³Burcham, Frank W., Jr., Trindel A. Maine, and Thomas Wolf, *Flight Testing and Simulation of an F-15 Airplane Using Throttles for Flight Control*, NASA TM-104255, 1992.
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Fig. 1 NASA F-15 HIDECA flight research aircraft.



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Fig. 2 PCA features on the F-15 airplane.

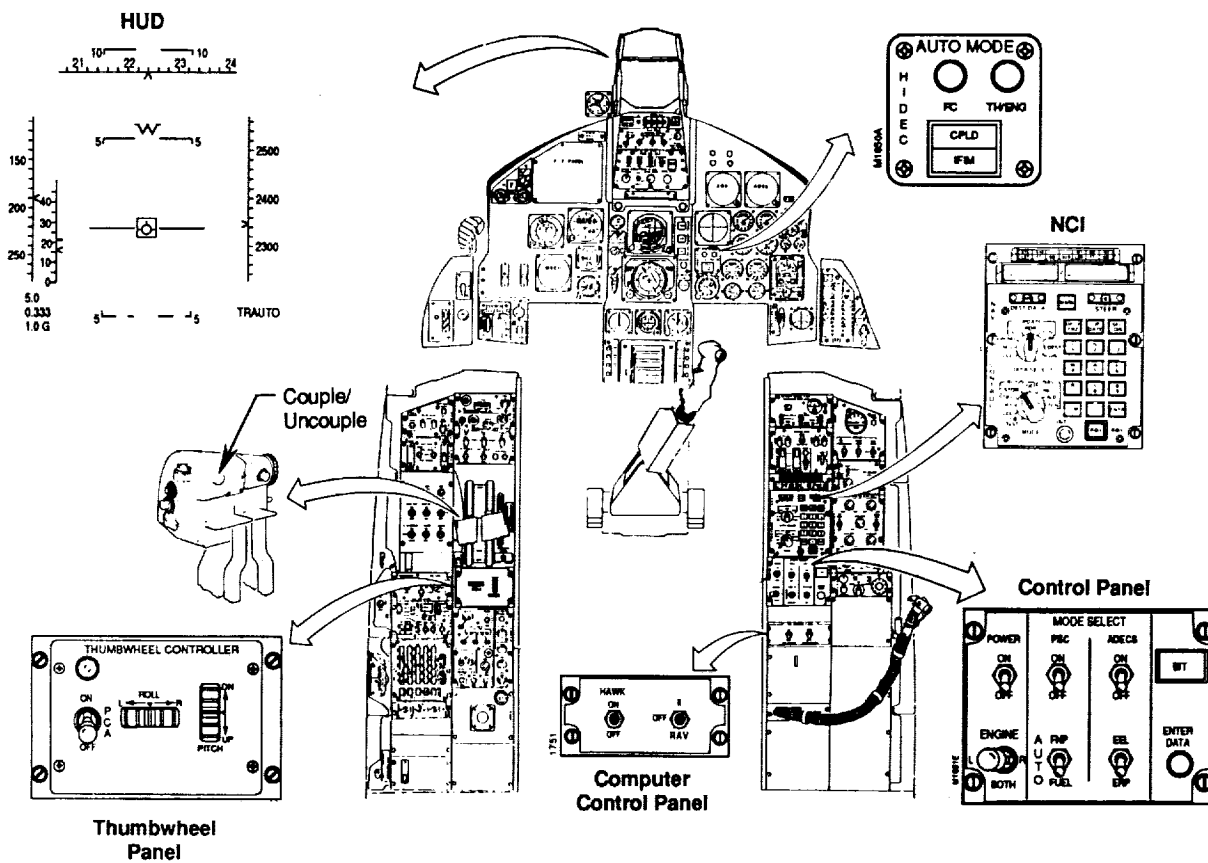


Fig. 3 F-15 PCA cockpit configuration.

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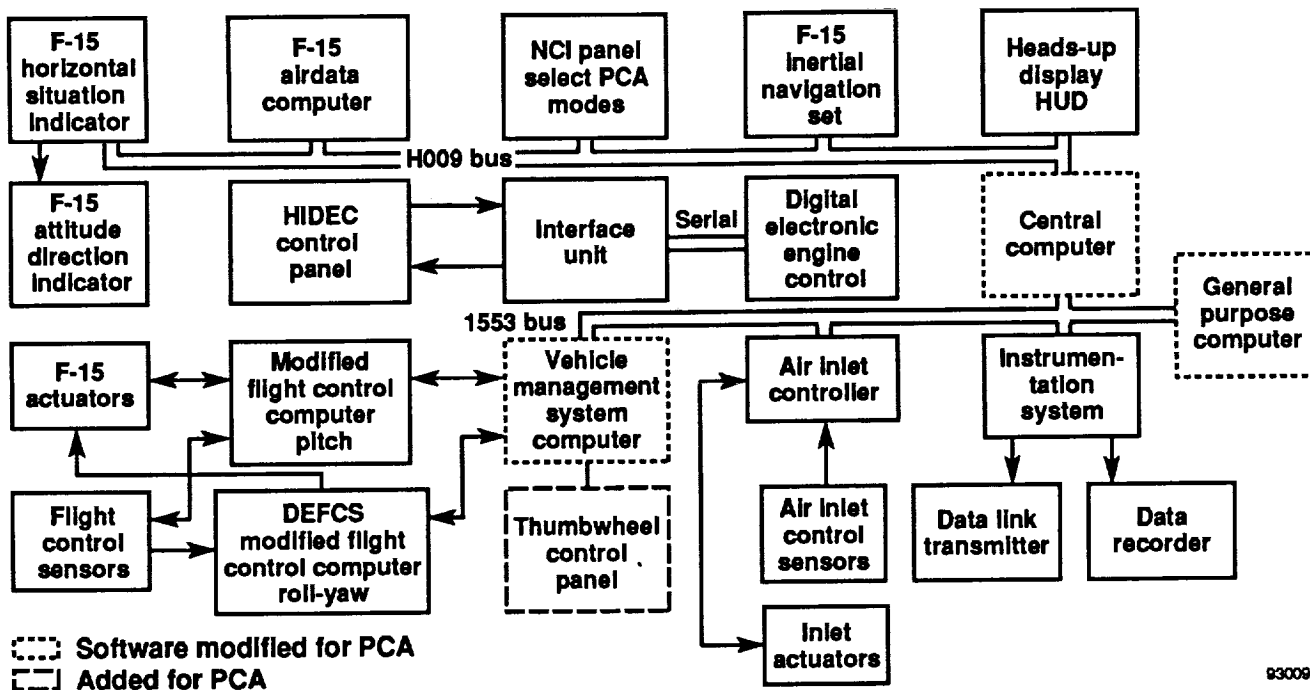


Fig. 4 PCA hardware block diagram.

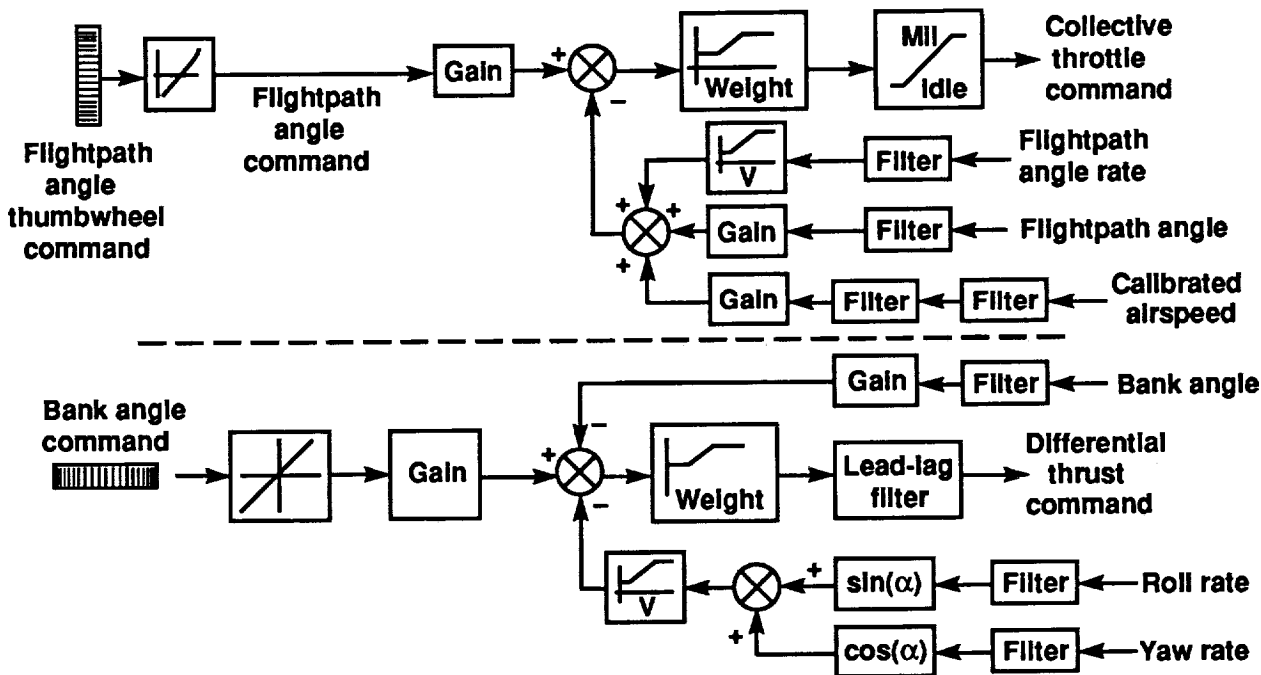


Fig. 5 Simplified block diagram of the F-15 PCA logic.

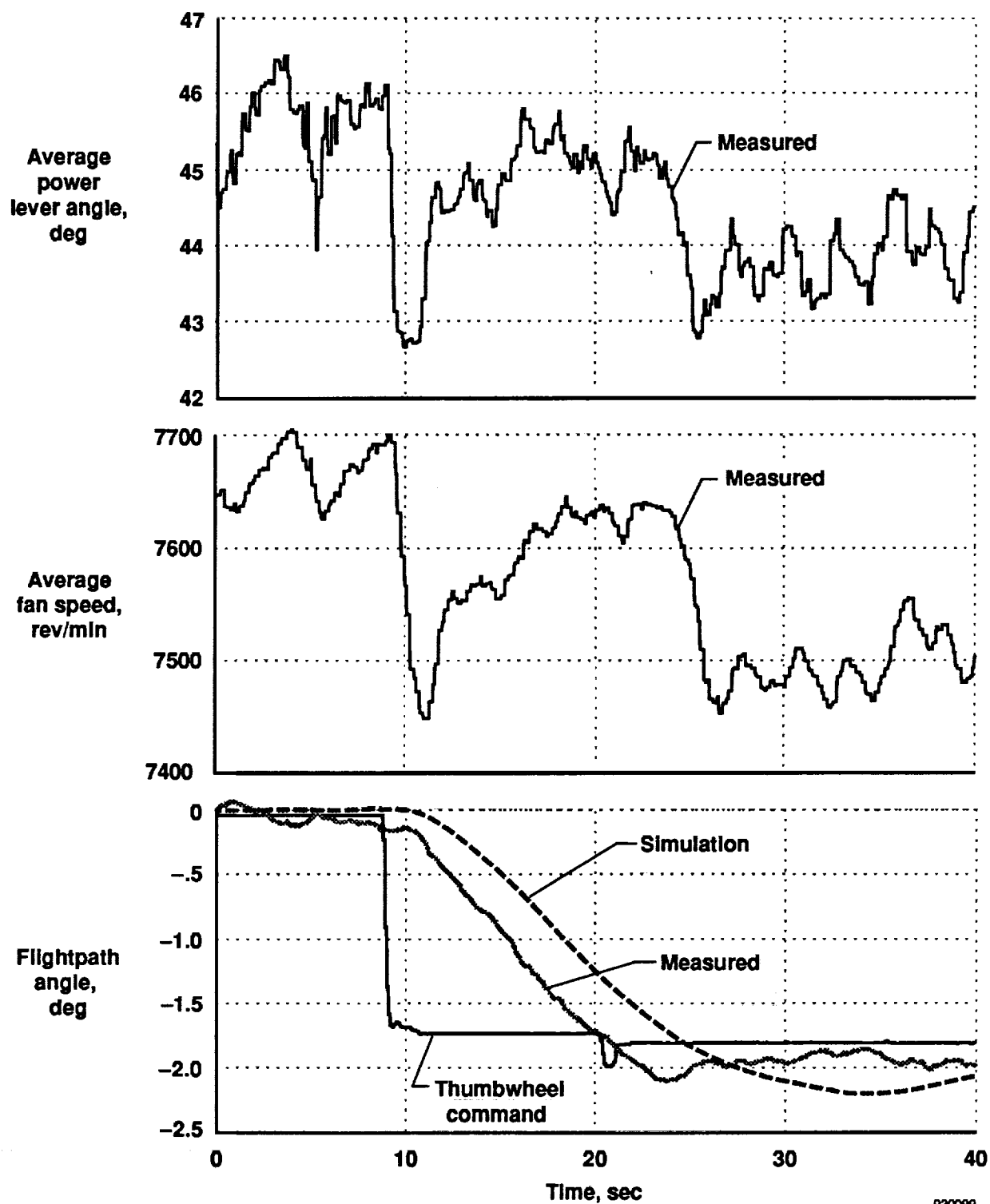
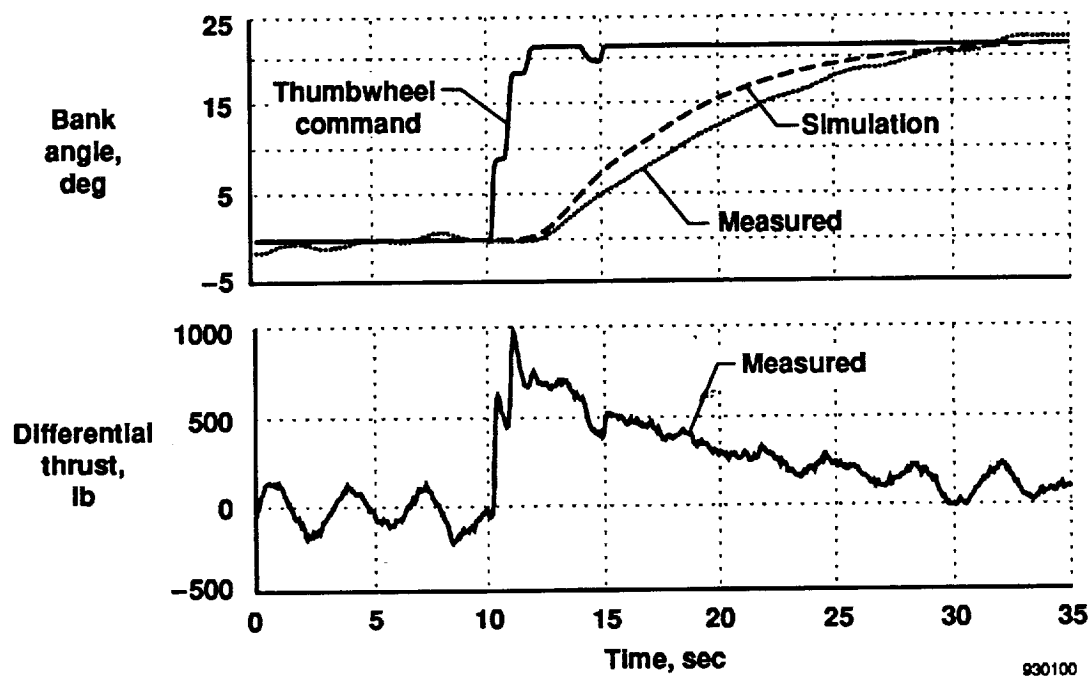
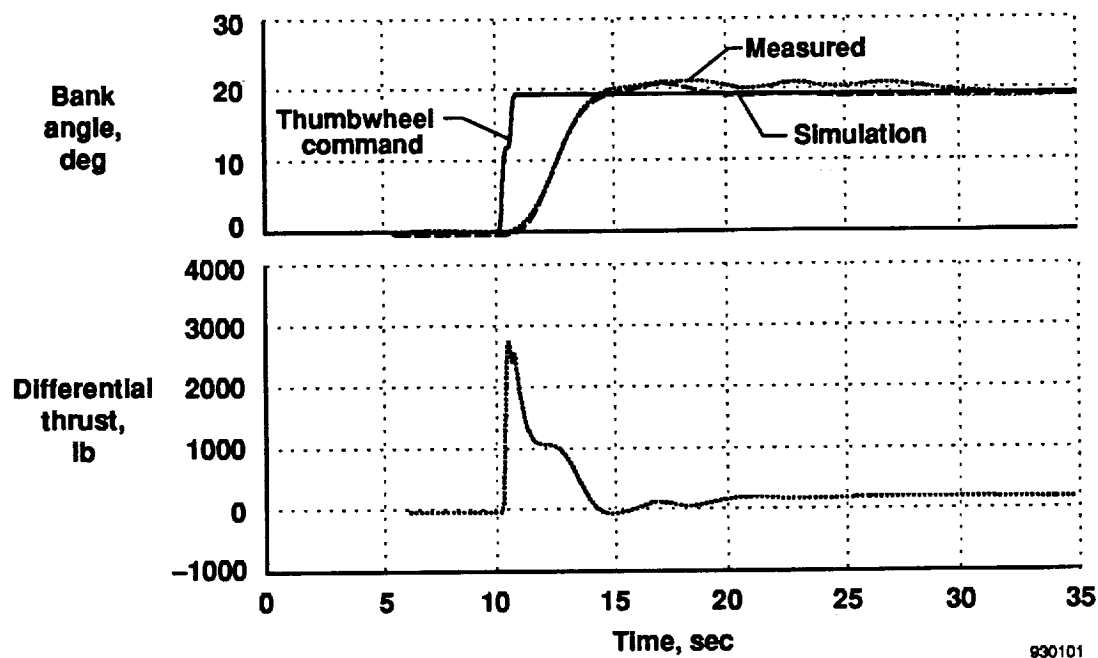


Fig. 6 Response of the F-15 PCA system to a flightpath angle step from 0 to -1.8° .



(a) Initial bank angle control logic.



(b) Improved bank angle control logic.

Fig. 7. Effect of a step bank angle command on bank angle, 150 kts, flaps down.

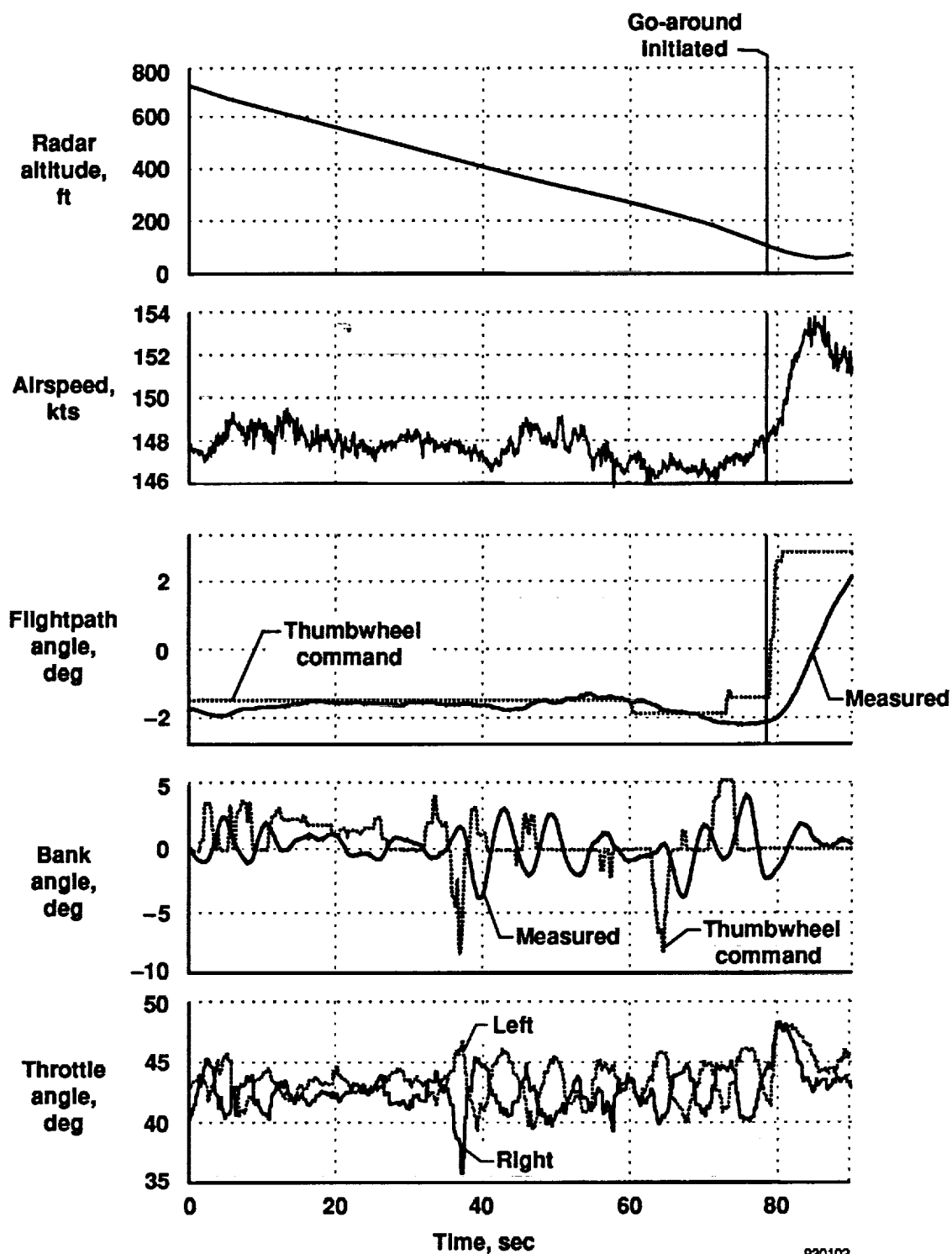
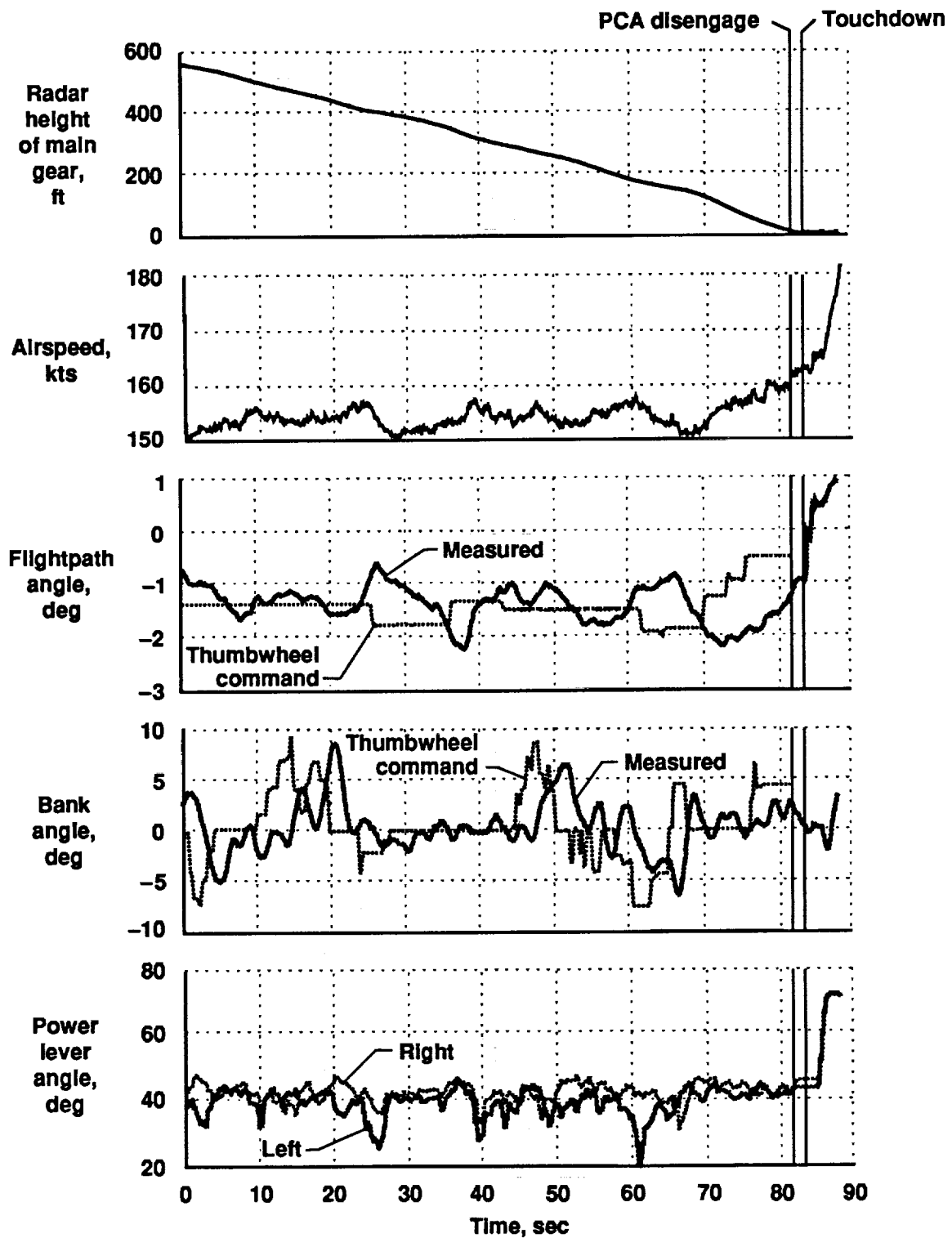


Fig. 8 Time history of a PCA approach and go-around.

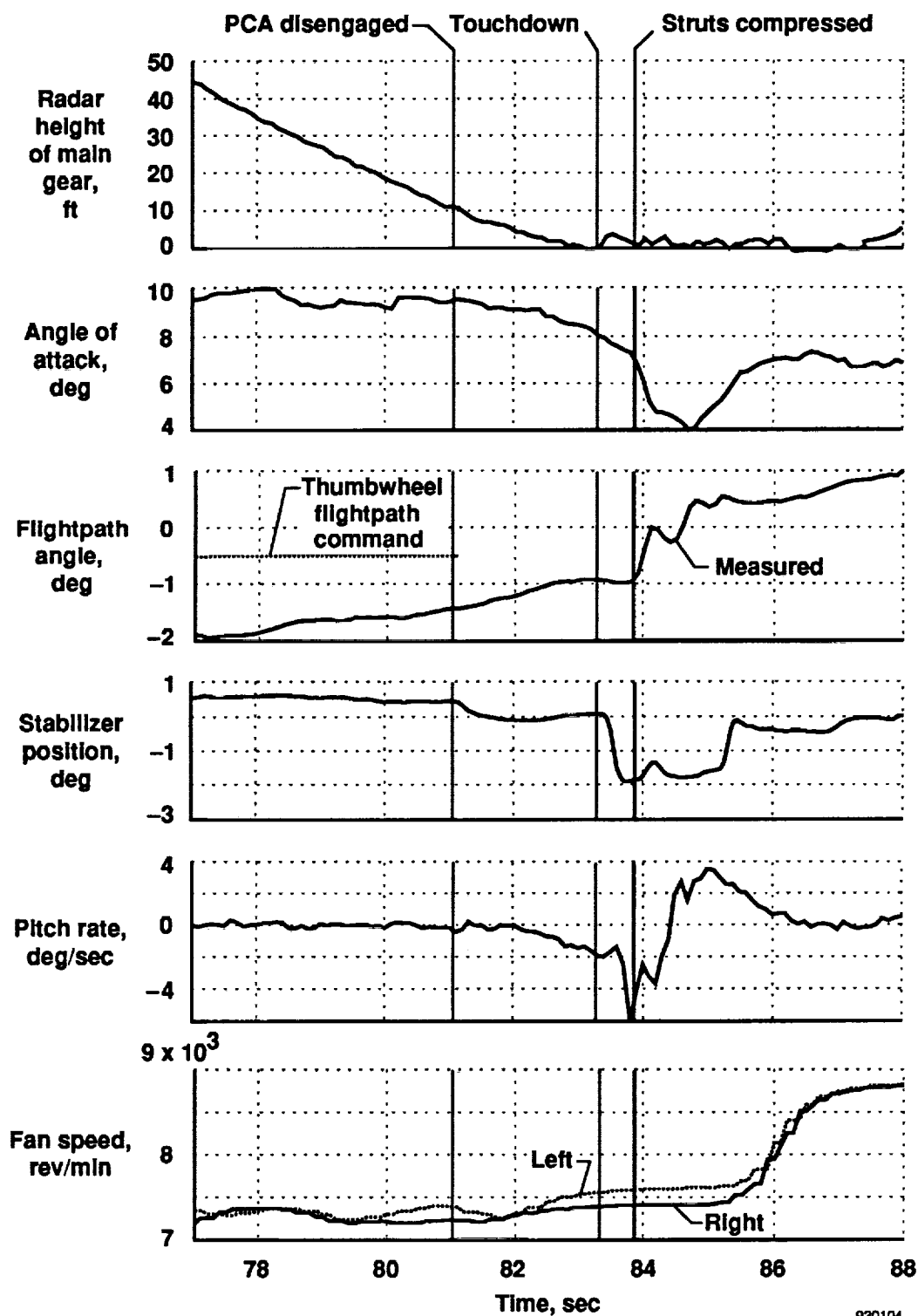
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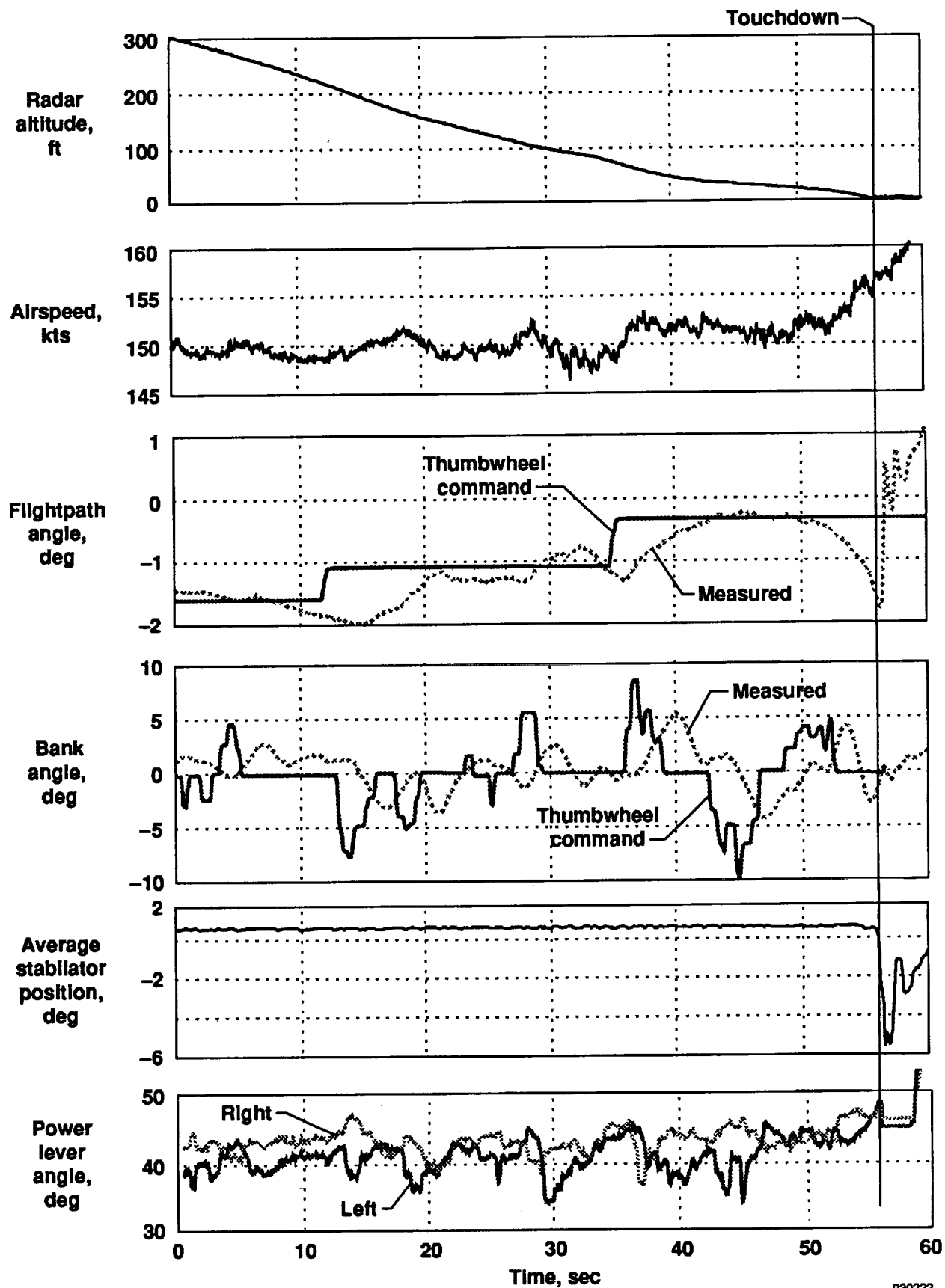
(a) 83 sec of landing approach

Fig. 9 Time history of F-15 PCA landing approach, flaps down.



(b) Last 6 sec of landing approach.

Fig. 9 Concluded.



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Fig. 10 Time history of PCA landing.

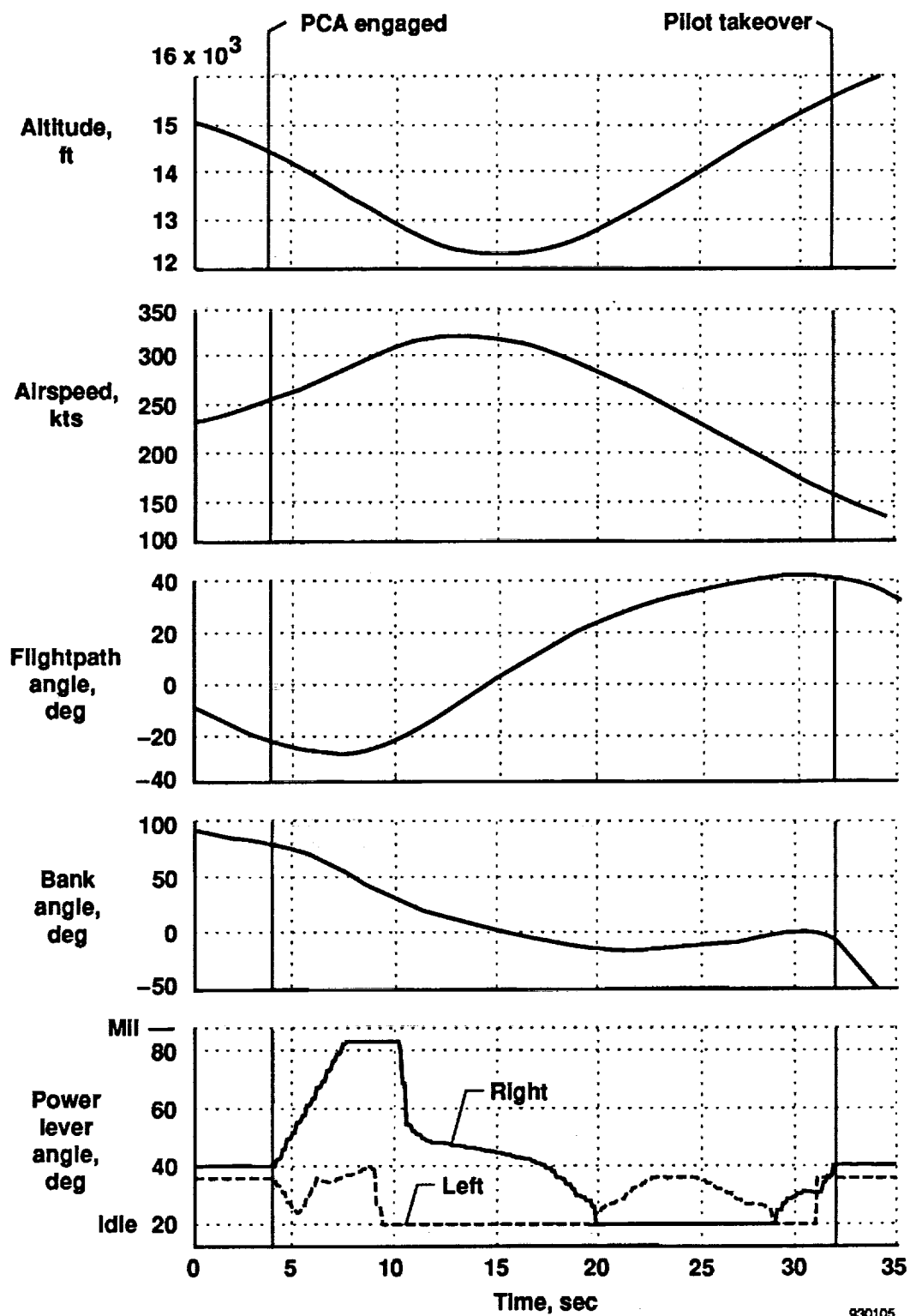


Fig. 11 Time history of F-15 PCA engagement at unusual attitude.

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